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CHANNEL INSTABILITY IN THE LOESS AREA OF THE MIDWESTERN UNITED STATES[1]

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ABSTRACT: The loess area of the midwestern United States contains thousands of miles of unstable stream channels that are undergoing system-wide channel-adjustment processes as a result of (1) modifications to drainage basins dating back to the turn of the 20th century, including land clearing and poor soil-conservation practices, which caused the filling of stream channels, and consequently (2) direct, human modifications to stream channels such as dredging and straightening to improve drainage conditions and reduce the frequency of out-of-bank flows. Today, many of these channels are still highly unstable and threaten bridges, other structures, and land adjacent to the channels. The most severe, widespread instabilities are in western Iowa where a thick cap of loess and the lack of sand- and gravel-sized bed sediments in many channels hinders downstream aggradation, bed-level recovery and the consequent reduction of bank heights, and renewed bank stability. In contrast, streams draining west-central Illinois, east-central Iowa, and other areas, where the loess cap is relatively thin and there are ample supplies of sand- and gravel-sized material, are closer to recovery. Throughout the region, however, channel widening by mass-wasting processes is the dominant adjustment process.
(KEY TERMS: unstable channels; loess channels; degradation; bank instability; shear strength.)

INTRODUCTION

The dynamic nature of alluvial streams signifies the ability to adjust to changes imposed on the fluvial system, be they natural or a result of human activities. Channel adjustments migrate upstream and downstream in an attempt to offset the disturbance by altering aspects of their morphology, sediment load, and hydraulic characteristics. Under "natural" conditions, in geologically stable areas such as the midwestern United States, the processes of erosion and deposition might occur at such low rates and over such extended periods of time, that they can be virtually imperceptible. Human and natural factors or disturbances, however, combine to accelerate and exacerbate these processes, and as a result, rapid and observable morphologic changes occur as the channel attempts to offset the disturbance and return to an equilibrium condition. Adjustments to human disturbances can involve short time scales (days) and limited spatial extents (a stream reach), or longer periods of time (scores to hundreds of years) and entire fluvial systems, depending on the magnitude, extent, and type of disturbance (Williams and Wolman, 1984; Simon, 1994).

In the highly erodible loess area of the midwestern United States (Figure 1), human disturbances to flood plains and upland areas culminating near the turn of the 20th century resulted in channels being choked with sediment and debris. Beginning about 1910, channels were enlarged and straightened throughout the region to alleviate frequent and prolonged flooding of bottomlands (Speer *et al.,* 1965). Over the next 80 years, accelerated channel erosion and the formation of canyon-like stream channels have resulted in severe damage to highway structures, pipelines, fiberoptic lines, and land adjacent to the stream channels. Accelerated stream-channel degradation has resulted in an estimated $1.1 billion in damages to infrastructure and the loss of agricultural lands since the turn of the century in western Iowa (Baumel, 1994). A survey of 15 counties in northwestern Missouri identified 957 highway structures as damaged by channel degradation. Degradation and channel widening in the loess area led to the collapse of several bridges in West Tennessee (Robbins and Simon, 1983), southwest Mississippi (Wilson, 1979), Missouri (Emerson,

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1971), and southeast Nebraska. The 1993 floods in the midwestern United States focused additional attention on channel-stability problems in the loess area because scores of bridges were either closed or failed during and immediately after the floods.

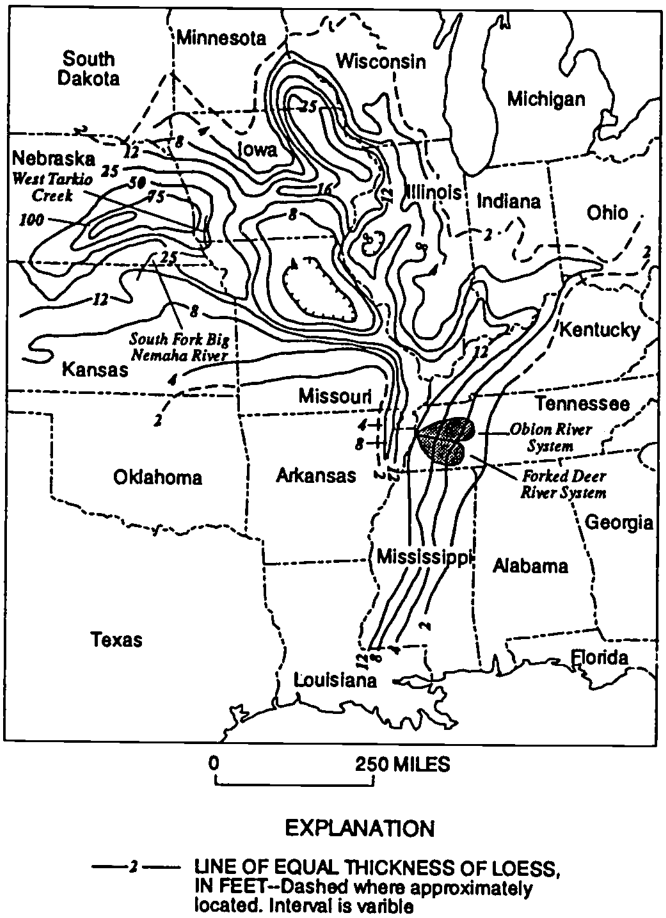

Figure 1. Location Map of Loess Area of Midwestern United States and Thickness of Loess, in feet (modified from Luttenegger, 1987).

Channel degradation in some streams has resulted in a fourfold increase in channel depth [6 meters (m)] and an almost fivefold increase in channel width (30 m) since the middle of the 19th century (Piest *et al.*, 1976; 1977). Erosion rates from two severely degraded silt-bed streams in western Iowa were calculated at 133,000 and 147,000 tonnes/year (Ruhe and Daniels, 1965; Piest *et al.*, 1976). About 193,000 tonnes/year of channel materials were discharged from 12.4 kilometers (km) of Hotophia Creek, northern Mississippi, between 1958 and 1976 (Little and Murphey, 1981). In the 20 years of channel adjustment following modification of about 145 km of channels in the Obion River System, West Tennessee, an estimated 6.3 million m^3 of channel sediments were eroded and transported out of the system (11 million tonnes/year; Simon, 1989a). About 10 million tonnes/year were discharged from the Forked Deer River System, West Tennessee between the early 1970s and 1987. On average, about 18 percent of this material was eroded from the channel bed, the remainder coming from the channel banks (Simon, 1989a).

The purpose of this study, which was sponsored by the Federal Highway Administration, was to assess the general magnitude and extent of channel-stability problems in the loess area of the midwestern United States (Figure 1). This region represents a "worst-case" scenario where easily erodible soil has combined with extensive human disturbance to produce highly unstable stream-channel systems. Reconnaissance-level observations were made from a low-flying aircraft or by driving and noting stability problems along unstable streams in west, east-central, and southeastern Iowa; southeastern Nebraska; west-central Illinois; northeastern Kansas; and northwestern Missouri. Silt-bedded West Tarkio Creek, southwestern Iowa and northwestern Missouri, and to a lesser extent, two sites on the South Fork Big Nemaha River, Nebraska were investigated in more detail to show typical channel changes. The sand-bedded Obion River System, West Tennessee, was studied previously (Simon, 1989a, 1989b, 1989c; Hupp, 1992; Simon and Hupp 1992; Simon, 1994).

SYSTEM WIDE CHANNEL INSTABILITY

Channel instability in the loess area of the midwestern United States involves entire drainage systems. Common adjustment processes affecting these fluvial systems include: upstream progressing degradation; downstream aggradation; channel widening, and to a limited extent, channel narrowing in the downstream-most reaches; and changes in the quantity and character of the sediment load. These processes differ from localized processes such as scour and fill, which can be limited in magnitude, as well as in spatial and temporal scale. Scour and fill can occur over periods of hours to days and affect localized areas and bridges in response to stormflow. In contrast, the processes of aggradation and degradation, which represent systematic changes in bed elevation over a period of years (Mackin, 1948), can affect long stream reaches, entire stream lengths, or whole stream systems. In fact, longer-termed adjustment processes can, by themselves, instigate or exacerbate local scour problems (Robbins and Simon, 1983). Whether bed erosion occurs as scour, as degradation, or in combination, sufficient bed-level lowering can lead to bank instabilities and to changes in channel pattern. Thus, attempts at mitigation of channel instabilities must consider the site or reach in question as it fits into the broader spatial and temporal scheme of system wide adjustment and channel evolution. Addressing only local symptoms at a site will often be insufficient to mitigate an instability problem.

FACTORS CONTROLLING CHANNEL STABILITY IN THE LOESS AREA

Factors that affect channel stability can be conceptualized in terms of (1) the resistance of the channel boundary to erosion and (2) the forces acting on the channel to erode the boundary. If these opposing tendencies are balanced, the channel is considered to be in equilibrium, and no net erosion or deposition will occur with time.

Vertical channel instabilities can be considered as a result of a disruption to the equilibrium (balance) between available stream power (the discharge-gradient product) and the discharge of bed-material sediment (Lane, 1955; Bull, 1979):

$$\mathbf{Q\ S \propto Q_s\ d_{50}} \qquad (1)$$

where $\mathbf{Q}$ = bankfull discharge, $\mathbf{S}$ = channel gradient, $\mathbf{Q_s}$ = bed-material discharge, and $\mathbf{d_{50}}$ = median grain size of bed material.

Equation (1) indicates that if available stream power is increased by an increase in the bankfull discharge or the gradient of the stream, there would be an excess amount of stream power relative to the discharge of bed-material sediment. Additional sediment would be eroded from the channel bed resulting in: (1) an increase in bed-material discharge to an amount commensurate with the heightened stream power, and (2) a decrease in channel gradient and, consequently, stream power as the elevation of the channel bed is lowered. A similar response would be expected from a decrease in the erosional resistance of the channel boundary or a decrease in the size of bed-material sediment (assuming it is not cohesive). Because channel banks in the loess area of the midwestern United States are composed predominantly of silt, non-cohesive sand or gravel banks contributing bed-material sediment are not considered here. In contrast, a decrease in available stream power or an increase in the size or discharge of bed-material sediment would lead to aggradation on the channel bed. Factors that increase hydraulic roughness will decrease flow velocity and, therefore, discharge and stream power. For example, proliferating vegetation on stream banks causes slower velocities and reduced stream power in the near-bank zone.

Lateral (bank) instabilities are also considered in terms of force and resistance. Because loess-channel banks are fine grained (silty), low to moderately cohesive (Lohnes and Handy, 1968; Lutenegger, 1987; Simon, 1989b), and generally erode by mass failure, the shear strength of the bank material represents the resistance of the boundary to erosion. Shear strength comprises two components – cohesive strength and frictional strength. For the simple case of a planar failure of unit length, the Coulomb equation is applicable:

$$\mathbf{S_r = c + (N - \mu)\tan\phi} \qquad (2)$$

where $\mathbf{S_r}$ = shear stress at failure, in kilopascals (kPa); $\mathbf{c}$ = cohesion, in kPa; $\mathbf{N}$ = normal stress on the failure plane, in kPa; μ = pore pressure, in kPa; and ϕ = friction angle, in degrees.

Also

$$\mathbf{N = W(\cos\theta)} \qquad (2a)$$

where $\mathbf{W}$ = weight of the failure block, in kN/m^2; and θ = angle of the failure plane, in degrees.

The gravitational force acting on the bank is:

$$\mathbf{W \sin\theta} \qquad (3)$$

Factors that decrease the erosional resistance ($\mathbf{S_r}$), such as excess pore pressure from saturation and the development of vertical tension cracks, favor bank instabilities. Similarly, increases in bank height by bed degradation and bank angle by undercutting favor bank failure by causing the gravitational component to increase. In contrast, vegetated banks are generally drier and provide improved bank drainage, which enhances bank stability (Thorne, 1989). Plant roots provide tensile strength to the soil that is generally strong in compression, resulting in reinforced earth (Vidal, 1969) that resists mass failure, at least to the depth of vegetation roots. However, the added weight of woody vegetation on a bank acts as a surcharge and can have negative effects on bank stability by increasing the downslope component of weight, particularly on steep banks.

Natural Factors

The predominant natural factors regarding channel-stability problems in the loess area of the midwestern United States are related to the relative resistance to erosion of the loess, and the distribution of loess around and beneath the channel boundary. Although loess can stand in tall vertical cliffs when dry, it tends to be highly erodible when wetted by streamflow or by raindrop impact. Once disturbed, channels with beds of loess-derived alluvium generally incise rapidly and, without an ample supply of sand or gravel, tend to be some of the deepest in the region. Because the fluvial transport of fine-grained sediments such as silt is not only controlled by the hydraulic properties of the streamflow but also by the supply of silt delivered to the flow from channel or upland sources, little silt is deposited in downstream reaches to aid in bed-level recovery. Channels that cut through the loess cap and entrain coarser sand and gravel deposits below will, on average, recover quicker from disturbances because there is a supply of hydraulically-controlled material that is likely to be deposited in downstream reaches, causing aggradation and the consequent decrease in bank heights.

The relatively low resistance (shear strength) of the loess bank material to erosion by mass failure is an important factor in channel evolution in the region. The mean values of cohesion and friction angle for 22 sites throughout the region are 9.7 kPa and 35.4°, respectively (Lutenegger, 1987). The mean values for 14 shear-strength tests in Iowa bluff-line streams are 8.9 kPa and 24.9° (Lohnes and Handy, 1968). Data indicate that, on average, loess in Kansas and Nebraska are considerably more cohesive, ranging from 35 to 69 kPa (Turnbull, 1948; Lohnes and Handy, 1968). Cohesion and friction-angle values obtained in Mississippi for loess-derived sediments range from 9.2 to 34 kPa, and from 16 to 35°, respectively (Turnipseed and Wilson, 1992; Wilson and Turnipseed, 1993, 1994). The mean value of cohesion reported for 23 borehole shear-strength tests conducted in loess-derived sediments in northern Mississippi is relatively high, (54 kPa) by Thorne *et al.* (1981). This value may be unrealistically high, owing to additional cohesive strength provided by negative pore-water pressures. The mean friction angle in these Mississippi tests is 21°.

A study of streambank stability in West Tennessee disclosed a mean cohesive strength of 8.7 kPa, and a mean friction angle of 30.1° (168 tests; Simon, 1989c). The West Tennessee tests were taken during summer low-flow conditions when the channel banks were driest and, therefore, the most resistant to mass failure. Nevertheless, the mean ambient degree of saturation was 86 percent, leaving the channel banks vulnerable to complete saturation during wet periods. Upon saturation and the generation of excess pore pressures (values of μ in Equation 2 greater than the steady-state values as determined by the "normal" position of the water table), shear strength values can decrease. By Equation (2), a continued increase in μ can result in the frictional component of shear strength becoming zero, leaving only the cohesion component to resist mass failure. In West Tennessee, the cohesion component, on average, comprises only about 10 percent of the strength of the loess-derived channel banks (Simon, 1989b) and, following saturation and the generation of excess pore pressures, is often insufficient to resist mass failure. Along channels deepened by degradation, mass failure occurs on the recession of river stage as the banks lose the support afforded by the water in the channel.

Established woody vegetation on streambanks can enhance bank stability but only if (1) degradation does not create bank heights and angles in excess of the critical shear-strength conditions of the bank material, and (2) rooting depths extend past the depth of the failure plane. Experiments on live roots of riparian sweet gum trees in northern Mississippi disclose tensile strengths of 5 MPa for 10 mm-diameter roots to 22 MPa for 2 mm-diameter roots. Similar tests on the roots of sycamore trees disclosed tensile strengths ranging from 15 MPa to 65 MPa for root diameters of 10 mm and 2 mm, respectively. The reinforcement provided by these roots can represent a significant contribution to bank strength if there are enough roots crossing a potential failure plane.

Human Factors

Human factors related to channel-stability problems can often be considered as disruptions or disturbances to the "natural" balance between the available erosional force acting on the channel boundaries and the erosional resistance provided by those boundaries. Such disturbances can be imposed directly on the channel as in the case of dredging or channel straightening, or can be indirect as in the case of land clearing. In the loess area of the midwestern United States, direct and indirect disturbances have contributed to the channel-stability problems of the region.

Large tracts of land were cleared for cultivation during settlement of the region prior to and after the Civil War (Ashley, 1910; Brice, 1966; Piest *et al.*, 1977). Stream courses were tortuous with sinuosities ranging from about 3 to 4, with valley slopes in the order of 10^{-4} to 10^{-3} m/m (Moore, 1917; Speer *et al.*, 1965). Channel gradients from trunk streams in southeastern Nebraska and West Tennessee were about 1.2 and 1.1 x 10^{-4} m/m, respectively (U.S. Army Corps of Engineers, 1907; Moore, 1917). The removal of grasses and woody vegetation resulted in reduced water interception and storage, increased rates of surface runoff, erosion of uplands, and gullying of flood plains and terraces. Surface runoff and peak-flow rates in western Iowa are estimated to have increased 2-3 times and 10-50 times, respectively, when compared to estimates of presettlement amounts (Piest *et* *al.*, 1976, 1977). The removal of woody vegetation from streambanks resulted in decreased hydraulic roughness, increased flow velocities and stream power, and contributed to increased peak discharges. In combination, these factors caused extensive downcutting (Piest *et al.*, 1976). Much eroded material was deposited in channels, resulting in a loss of channel capacity and frequent and prolonged flooding of agricultural lands (Morgan and McCrory, 1910; Moore, 1917; Piest *et al.*, 1976). Moore (1917) reports that aggradation was almost continuous along the trunk streams of southeastern Nebraska.

As a result of ubiquitous channel filling, local drainage districts implemented programs to dredge, straighten, and shorten stream channels (channelize) to reduce flooding and thereby increase agricultural productivity (Hidinger and Morgan, 1912; Moore, 1917). Work was undertaken in southeastern Nebraska, West Tennessee, and west-central Illinois around 1910 (Moore, 1917; Speer *et al.*, 1965); and in western Iowa around 1920 (Lohnes *et al.*, 1980). In many areas, this work increased channel gradients by about an order of magnitude (Moore, 1917; Simon, 1994). Entire lengths of trunk streams were channelized in southeastern Nebraska and in West Tennessee. By the 1930s most streams tributary to the Missouri and Mississippi Rivers in the loess area of the midwestern United States had been dredged and straightened (Speer *et al.*, 1965; Piest *et al.*, 1976; Lohnes *et al.*, 1980; Simon, 1994). In many parts of the region these activities were conducted periodically throughout the 1960s and 1970s as additional tributaries were channelized and because some previously dredged channels filled with eroded sediment from upstream reaches (Lohnes *et al.*, 1980; Simon, 1994).

Dredging and straightening significantly increased bankfull discharge and channel gradient, resulting in a proportionate increase in bed-material discharge and rapid morphologic changes (Equation 1). These changes included upstream degradation, downstream aggradation (in the sand-bedded streams), and bank instabilities along altered streams and adjacent tributaries. In combination with the low resistance to erosion exhibited by the loess-derived channel materials, it was the increase in the erosional force (stream power) by channel dredging and straightening near the turn of the 20th century that caused the deep entrenchment, general states of instability, and present-day problems in the channel systems in the loess area of the midwestern United States.

STAGES OF CHANNEL EVOLUTION

Researchers in fluvial geomorphology have noted that alluvial channels in different environments, destabilized by different natural and human-induced disturbances, pass through a sequence of channel forms with time (Davis, 1902; Ireland *et al.*, 1939; Schumm and Hadley, 1957; Daniels, 1960; Emerson, 1971; Keller, 1972; Elliot, 1979; Schumm *et al.*, 1984; Simon and Hupp, 1986; Simon, 1989a; Figure 2; Table 1). These systematic temporal adjustments are collectively termed "channel evolution" and permit interpretation of past and present channel processes, and prediction of future channel processes. One of the most popular of these schemes is the five-stage channel evolution model of Schumm *et al.* (1984), which was developed from morphometric data acquired on Oaklimiter Creek, northern Mississippi (Figure 3). Another channel evolution model was developed independently by the U.S. Geological Survey at the same time from data collected north of the Mississippi-Tennessee state line from a 10,600 mi^2 area of West Tennessee (Simon and Hupp, 1986; Simon, 1989b; 1994; Figure 2a). The West Tennessee model has six stages, is based on shifts in dominant adjustment processes, and is associated with a model of bank-slope development (Figure 2b). Differences in the Schumm *et al.*, (1984) model and the Simon and Hupp (1986) model are (Figures 2a and 3):

1. Stage II of the Simon and Hupp (1986) model represents the constructed/disturbed state and can be considered as an almost instantaneous condition prior to adjustment; more importantly,
2. The onset of channel widening by mass-wasting processes is associated with aggradation on the channel bed in the Schumm *et al.* (1984) model (Stage III; Figure 6-7, p. 128). In the Simon and Hupp (1986) model, mass failures of bank material are identified earlier in the adjustment sequence (Stage IV), prior to the onset of aggradation when the channel is still degrading its bed.

In alluvial channels, disruption of the dynamic equilibrium often results in some amount of upstream channel degradation and downstream aggradation. Using the Simon and Hupp (1986) model, one can consider the equilibrium channel as the initial, predisturbed stage (I) of channel evolution, and the disrupted channel as an instantaneous condition (Stage II). Rapid channel degradation of the channel bed ensues as the channel begins to adjust (Stage III, Figure 2a). Degradation flattens channel gradients and consequently reduces the available stream power for given discharges with time. Concurrently, bank

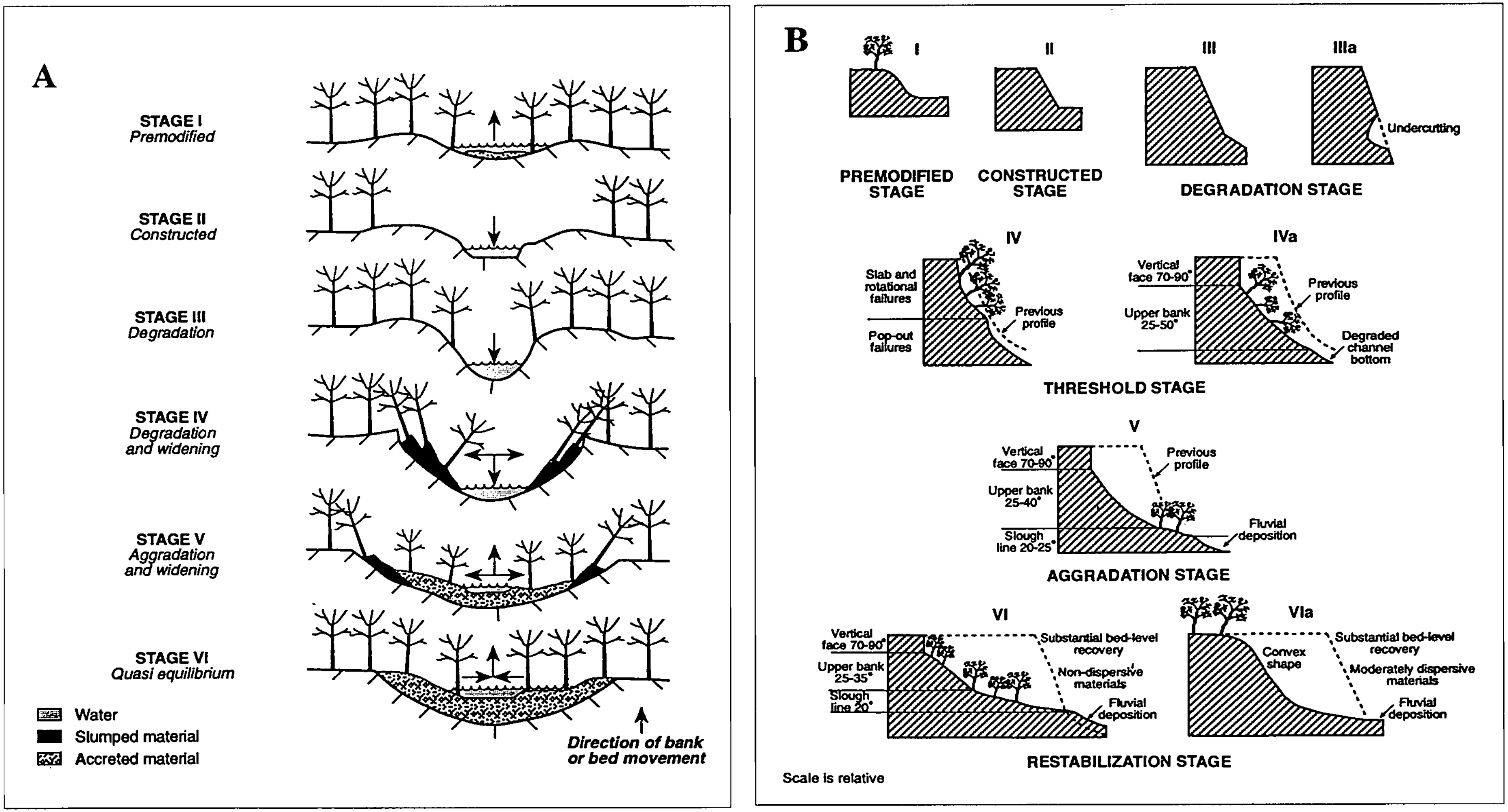

Figure 2. Six-Stage Models of (A) Channel Evolution and (B) Bank-Slope Development for Disturbed Alluvial Channels Developed in West Tennessee (Modified from Simon and Hupp, 1986; Simon, 1989b).

TABLE 1. Stages of Channel Evolution (from Simon and Hupp, 1986; Simon, 1989b).

Stage		Dominant Processes			
Number	Name	Fluvial	Hillslope	Characteristic Forms	Geobotanical Evidence
I	Premodified	Sediment transport; mild aggradation; basal erosion on outside bends; deposition on inside bends.	–	Stable, alternate channel bars; convex top-bank shape; flow line high relative to top bank; channel straight or meandering.	Vegetated banks to low-flow line.
II	Constructed	–	–	Trapezoidal cross section; linear bank surfaces; flow line lower relative to top bank.	Removal of vegetation (?).
III	Degradation	Degradation; basal erosion on banks.	Pop-out failures.	Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank.	Riparian vegetation high relative to flow line and may lean towards channel.
IV	Threshold	Degradation; basal erosion on banks.	Slab, rotational and pop-out failures.	Large scallops and bank retreat; vertical face and upper bank surfaces; failure blocks on upper bank; some reduction in bank angles; flow line very low relative to top bank.	Tilted and fallen riparian vegetation.
V	Aggradation	Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks.	Slab, rotational and pop-out failures; low-angle slides of previously failed material.	Large scallops, bank retreat; vertical face, upper bank and slough line; flattening of bank angles; flow line low relative to top bank; development of new flood plain (?).	Tilted and fallen riparian vegetation; re-establishing vegetation on slough line; deposition of material above root collars of slough-line vegetation.
VI	Restabilization	Aggradation; further develment of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends; deposition of flood plain and bank surfaces.	Low-angle slides; some pop-out failures near flow line.	Stable, alternate bars; convex short vertical face on top bank; flatten-of bank angles; development of new flood plain (?); flow line higher relative to top bank.	Re-establishing vegetation extends up slough line and upper bank; deposition of material above root collars of slough-line and upper-bank vegetation; vegetation establishing on bars.

heights are increased and bank angles are often steepened by fluvial undercutting and by pore-pressure induced bank failures near the base of the bank. Thus, the degradation stage (III) is directly related to destabilization of the channel banks and leads to channel widening by mass-wasting processes (Stage IV) once bank heights and angles exceed the critical shear-strength conditions of the bank material. The aggradation stage (V) becomes the dominant trend in previously degraded downstream sites as degradation migrates further upstream because the flatter gradient at the degraded site cannot transport the increased sediment loads emanating from degrading reaches upstream. This secondary aggradation occurs at rates roughly 60 percent less than the associated degradation rate (Simon, 1992). These milder aggradation rates indicate that bed-level recovery will not be complete and that attainment of a new dynamic equilibrium (Stage VI) will take place through further (1) bank widening and the consequent flattening of bank slopes; (2) the establishment and proliferation of riparian vegetation that adds roughness elements, enhances bank accretion, and reduces the stream power for given discharges; and (3) further gradient reduction by meander extension and elongation.

The lack of complete bed-level recovery results in a two-tiered channel configuration with the original flood-plain surface becoming a terrace. Stormflows are, therefore, constrained within this enlarged channel below the terrace level resulting in a given flow having greater erosive power than when flood flows could dissipate energy by spreading across the flood

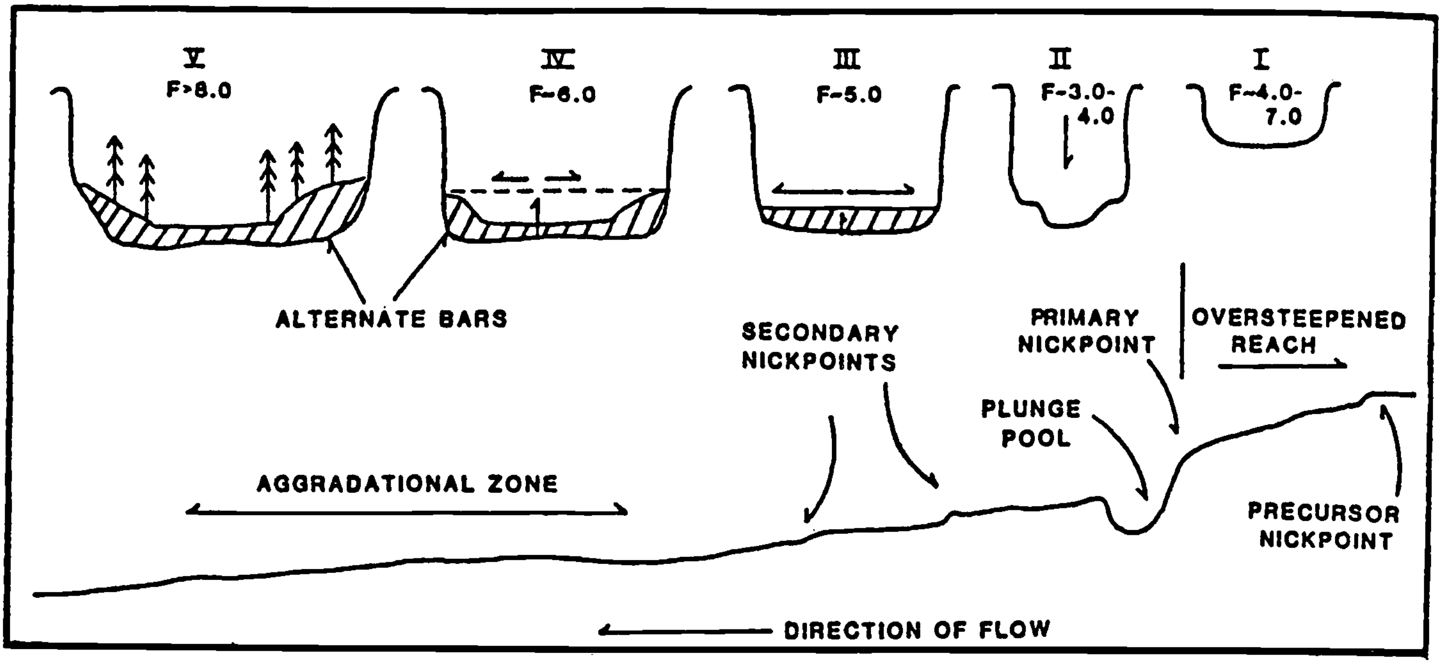

Figure 3. Five-Stage Model of Channel Evolution Developed on Oaklimiter Creek, Northern Mississippi (from Schumm *et al.*, 1984).

plain. This scenario is common in the loess area of the midwestern United States and poses serious problems for the stability and maintenance of bridges and other river-crossing structures.

Channel Evolution in the Loess Area of the Midwestern United States

In western Iowa, stage of channel evolution was identified by Hadish (1994) from aerial reconnaissance of 887 river kilometers in 1993 and 1590 km in 1994 using the Simon and Hupp (1986) model. Results show that for both years, 56 percent of the stream lengths were classified as stage IV (widening and mild degradation). Bed-level recovery (Stage V; aggradation and widening) is occurring along about 24 percent of the stream lengths, predominantly along the downstream-most reaches. This indicates that channel widening by mass-wasting processes is currently the dominant adjustment process in the degraded streams of western Iowa, occurring along about 80 percent of the observed stream reaches. Only 6 percent of the stream reaches were classified as being stable, either premodified (Stage I) or restabilized (Stage VI) (Hadish, 1994), indicating that about 94 percent of the stream lengths in western Iowa can be considered unstable.

Stage V conditions (aggradation and mass failures) appear to dominate much of the main stems of the easterly-flowing sand-bedded streams in southeastern Nebraska. However, because Stage IV conditions (mass failures with bed degradation) are common along tributary streams, channel widening by mass failures is the overall dominant adjustment process in southeastern Nebraska as well. A reconnaissance-level study conducted by the U.S. Army Corps of Engineers (1995) using the Simon and Hupp (1986) model confirmed and mapped these observations. Although the percentage of stream reaches in each stage of evolution was not calculated, a conservative estimate of the percentage of stream reaches experiencing mass failures is 75 percent. The north-facing banks on the easterly-flowing streams are generally more unstable, as indicated by fresh failure surfaces and a lack of established woody-riparian vegetation than south-facing banks in the same reach. This is probably related to (1) higher moisture contents, and (2) a greater incidence of freezing and thawing of the silty bank materials on the north-facing banks. In contrast to western Iowa where Stage III degrading conditions can be found in the upstream reaches of most tributary streams, in southeast Nebraska only small upstream tributaries near basin divides can be classified as Stage III.

In West Tennessee, about 65 percent of the 1,645 studied sites are unstable, with channel widening occurring at about 60 percent of them (Bryan *et al.*, 1995). In this part of the loess area, similar comparisons can be made between channel evolution in streams with silt beds (that dominate western Iowa) and those with sand beds (that dominate southeastern Nebraska). Tributaries of the largest, modified West Tennessee streams rise in unconsolidated sand-bearing formations that supply sand to the channels as bed material. Aggradation in downstream reaches occurs after 10-15 years of incision, and channel widening occurs at moderate rates (Simon, 1989b). In contrast, smaller tributary streams near the Mississippi River bluff have cut only into loess materials, have silty beds, and no source of coarse-grained material. To reduce erosional forces and stream power for a given discharge without a coarse-grained sediment supply for downstream aggradation, channel widening (Stage IV) may be the only mechanism for the silt-bed streams to recover (Simon, 1994). The silt-bed channels are the deepest and most rapidly-widening channels in West Tennessee and may take hundreds of years to recover. This is similar to the western Iowa silt-bed streams such as West Tarkio Creek where downcutting (Stages III and IV) has lasted for as much as 70 years and channel widening is widespread. These findings indicate that:

1. There is more coarse-grained sediment (sand and gravel) available for bed-material transport in southeastern Nebraska and West Tennessee than in western Iowa.
2. Channel evolution and recovery in southeastern Nebraska and West Tennessee is further advanced than in western Iowa because of plentiful supplies of sand.
3. Channel widening by mass-wasting processes dominates all areas.
4. Degradation can be expected to continue to migrate upstream in western Iowa tributaries.

This latter point is supported by data from western Iowa reported by Antosch and Joens (1979) that show depths below channel beds to coarse-grained material (sand and gravel) to exceed 5 m along the major drainageways. This is further supported by bed-material data collected during this study along two unstable creeks in western Iowa and along West Tarkio Creek in western Iowa and northwestern Missouri (Figure 1) that show a preponderance of silty bed material, except in the downstream-most reaches where some sand can be found.

Reconnaissance in west-central Illinois and east-central and southeastern Iowa disclosed many sinuous streams with bank failures and meander extension occurring on outside bends from the growth of point bars on the opposite, inside bank. This is typical of late Stage V and Stage VI channels. Bank heights did not appear to be nearly as high as in southeast Nebraska, or western Iowa where bank heights between 8 and 11 m are common. Assuming that channel modifications occurred in west-central Illinois and east-central and southeastern Iowa at about the same time as in western Iowa, it seems that many of the eastern loess-area streams have recovered more quickly probably because (1) the initial direct disturbance to the channel (dredging and/or straightening) may not have been as extensive as in other parts of the loess area, and (2) the thinner loess cap has been penetrated by the streams, exposing an ample supply of coarser sand and gravel.

REGIONAL SUMMARY

Sequences of channel evolution in the loess area of the midwestern United States are consistent in that similar disturbances near the turn of the 20th century initiated channel adjustment of entire fluvial systems. Although sequences of channel evolution are similar throughout the region, distinct differences in the amount of time required for streams to pass from one stage to the next, to begin to exhibit signs of recovery (establishing woody-riparian vegetation, stabilizing streambanks, and a meandering low-flow thalweg), and to attain a new equilibrium condition vary with the class of sediments comprising the channel bed and banks. For example, the degradation Stage (III) accounts for 10-15 years in the sand-bedded streams of West Tennessee but about 70 years in the silt-bedded streams of western Iowa. Rather than differentiate on the basis of geographical location, time-based differences in sequences of channel evolution channel are conceptualized on the basis of boundary sediments. Figure 4 is a schematic representation of changes in bed elevation and channel width with the associated stage of channel evolution for loess-area streams composed of different bed-material sediments for the period 1850-2000. Note that sand-bed streams filled with deposited sediments during the 1930s through the 1950s necessitating redredging and the clearing and snagging of downstream reaches. This additional channel work rejuvenated trunk and tributary streams, causing the sequence of channel evolution to begin again (Figure 4).

The sequence of channel evolution is less complicated for the silt-bedded streams of western Iowa and those smaller tributary streams of the region that cut only into loess sediments. In these cases, deep incision along trunk and tributary streams resulting from the initial channel work near the turn of the 20th century rapidly created bank heights in excess of the critical conditions of the material, causing a long period of bank instability and channel widening (Figure 4). Without significant reductions in bank heights by aggradation, channel widening by mass-wasting processes will continue into the next century until such time as (1) bank angles are reduced by successive failures in the same location, and (2) the channel becomes so wide that the frequency of bank-toe removal by fluvial action is reduced considerably.

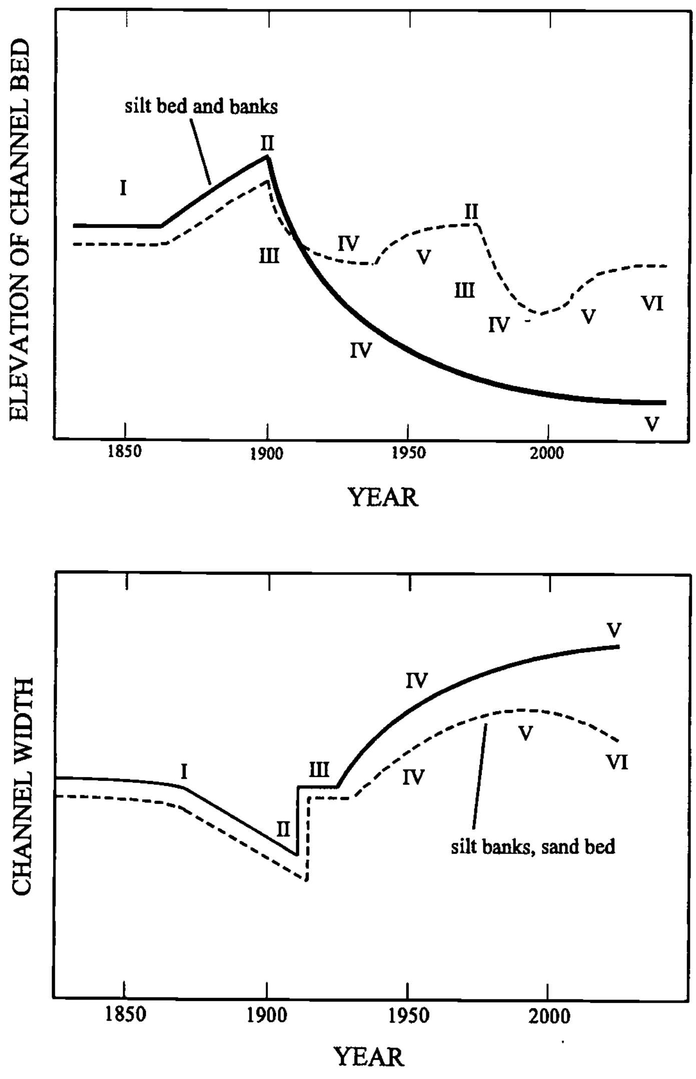

Figure 4. Schematic Representation of Typical Changes in Channel-Bed Elevation and Channel Width for Silt- and Sand-Bedded Streams in the Loess Area of the Midwestern United States for the Period 1850-2000.

1993 MIDWEST FLOODS

The 1993 Midwest floods did not result in a rejuvenation of previously unstable channel systems or accelerated bed-level adjustments. Gully extension into agricultural fields occurred. The predominant effect of the 1993 floods on channel instability of tributary streams in the loess area of the midwestern United States was channel widening. This occurred because of removal of toe material and prolonged saturation of channel banks, resulting in reduced shear strength and failures upon recession of storm flows. In straight reaches, low-cohesion channel banks up to 13.7 m-high fail readily at average rates of almost 2.1 m/yr. In reaches characterized by alternate bars, moderate flows erode low-bank surfaces on the opposite side of the channel resulting in steep bank angles, and accelerated rates of channel widening. The combination of alternate bar growth and accelerating widening on the opposite bank represent incipient meandering of the channel within the straightened alignment. Outside meander bends generally erode more rapidly than in straight reaches because of the buttressing effect of failed bank material is removed from the bank toe by fluvial action. This process was exacerbated by the 1993 floods.

WEST TARKIO CREEK, IOWA AND MISSOURI

Trends of channel change on West Tarkio Creek, Iowa and Missouri, were determined for the purpose of providing a quantitative measure of the rates and magnitudes of channel-adjustment processes in the region. West Tarkio Creek was selected because (1) it represents a typically unstable silt-bedded stream in the loess area of the midwestern United States that has undergone human disturbance, and (2) there is historical information available. Trends of channel adjustment were determined using historical bed-elevations, bank profiles, shear-strength tests, bed-material particle sizes, stages of channel evolution, and dendrochronologic evidence. Historical bed-level data were compiled from cross-section surveys and longitudinal profiles (Figure 5; Piest *et al.,* 1977; R. A. Lohnes, Iowa State University, written commun., 1994). Bed-elevation data for 1994 and the additional field data listed above were collected during the summer of 1994.

West Tarkio Creek incised in the middle 1800s as a result of increased runoff rates emanating from cleared lands (Piest *et al.,* 1977) and has been undergoing renewed channel adjustment since being straightened in about 1920. The channel displays the systematic variation of stage of channel evolution with distance upstream; aggradation (Stage V) in its downstream-most reaches merging to widening with mild degradation (Stage IV), to rapid degradation (Stage III), with increasing distance upstream (Figure 6). The dominant bed-material size class generally varies systematically with the stage of channel evolution and distance upstream – sand beds in aggrading reaches and silt beds in degrading reaches. Piest *et al.* (1977), describe stable reaches of West Tarkio

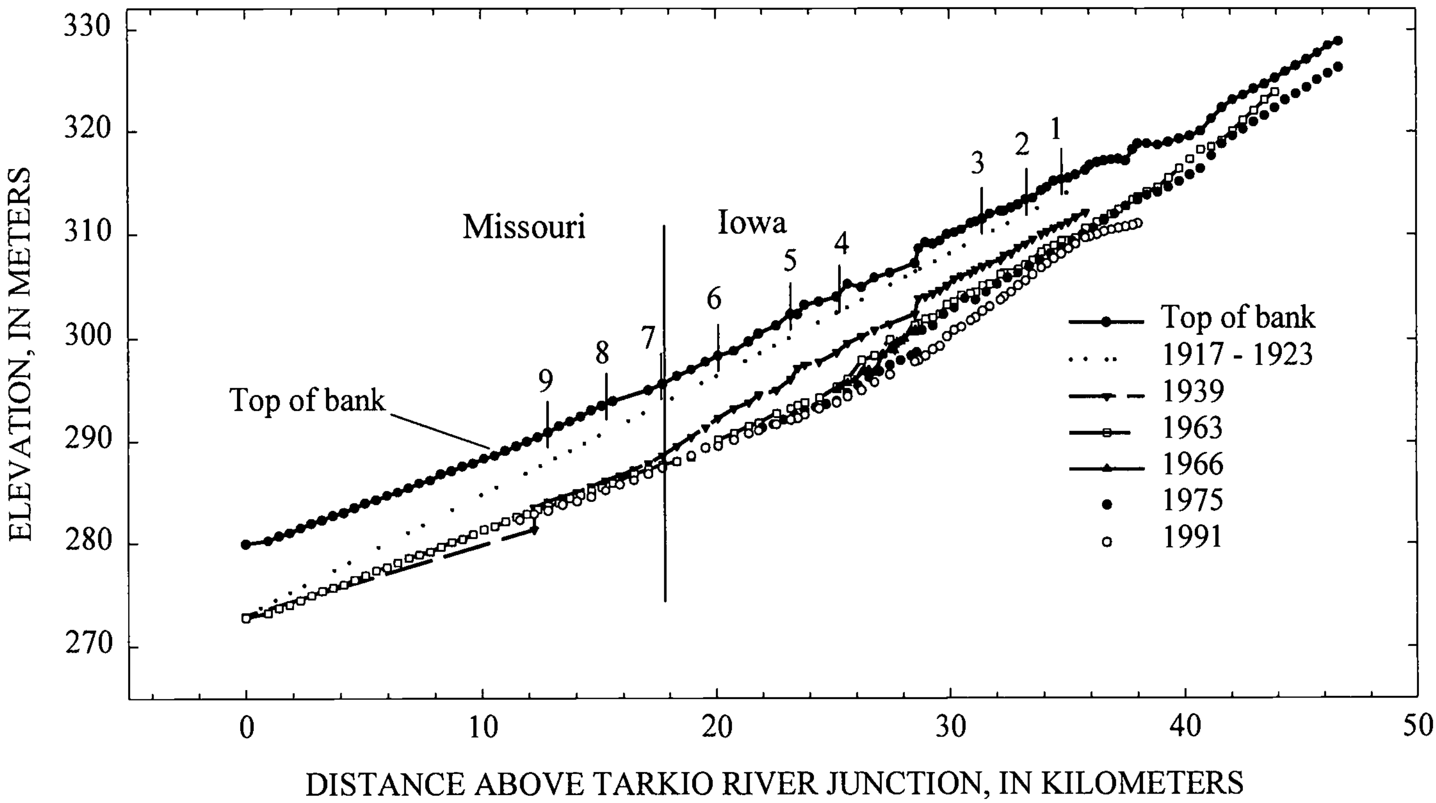

Figure 5. Profiles of West Tarkio Creek, Southwestern Iowa and Northwestern Missouri.

Creek in 1975 near its junction with the Tarkio River at a channel gradient of 0.0006 m/m. It is assumed that by stability the authors were referring to a lack of further downcutting. This implies that degradation lasted for about 55 years. By 1994, aggrading conditions on West Tarkio Creek extended at least 8 km into Iowa to the J52 bridge (Figure 6). Assuming that stable conditions in 1975 were at the confluence with the Tarkio River and were about 25 km further upstream in 1994 than in 1975 (19 years), a rate of migration of 1.3 km/yr is estimated.

The age of woody vegetation growing on streambanks is used as an indicator of bank conditions and the timing of renewed bank stability (Hupp and Simon, 1986, 1991; Hupp, 1992). It is probably coincidental, however, that the oldest riparian tree found at site T2 (Figure 6) is 19 years old. Still, this indicates that sections of streambanks have been stable for some time at Site T2. Ages and germination dates of the oldest streambank trees at other sites are shown in Figure 6, indicating the timing of renewed bank stability along at least some low-bank surfaces. Note that average, recent widening rates, as estimated from dendrochronologic evidence generally increase moving from Stage V conditions in downstream reaches to Stage IV conditions further upstream (Figure 6).

Bed-Level Adjustments

Trends of bed-level changes from 1920 to present were obtained by fitting historical data to an exponential decay equation modified from Simon (1992):

$$z / z_0 = a + (1 - a)\, e^{(-k t)} \qquad (4)$$

where z = elevation of the channel bed (at time "t"); z_0 = elevation of the channel bed at ($t_0 = 0$); a = dimensionless coefficient, determined by regression and equal to the dimensionless elevation (z/z_0) when Equation (1) becomes asymptotic, $a > 1$ = aggradation, $a < 1$ = degradation; 1-a = the total change in the dimensionless elevation (z/z_0) when Equation (1) becomes asymptotic, $(1 - a) > 0$ for degradation, $(1 - a) < 0$ for aggradation; k = coefficient determined by regression, indicative of the rate of change on the channel bed per unit time; and t = time since the year prior to the onset of the adjustment process, in years ($t_0 = 0$).

Although aggradation rates along the downstream-most eight miles of channel could not be estimated using this method because of a lack of recent survey data, accretion measured around trees on bank surfaces, particularly at the sites in Missouri, confirmed

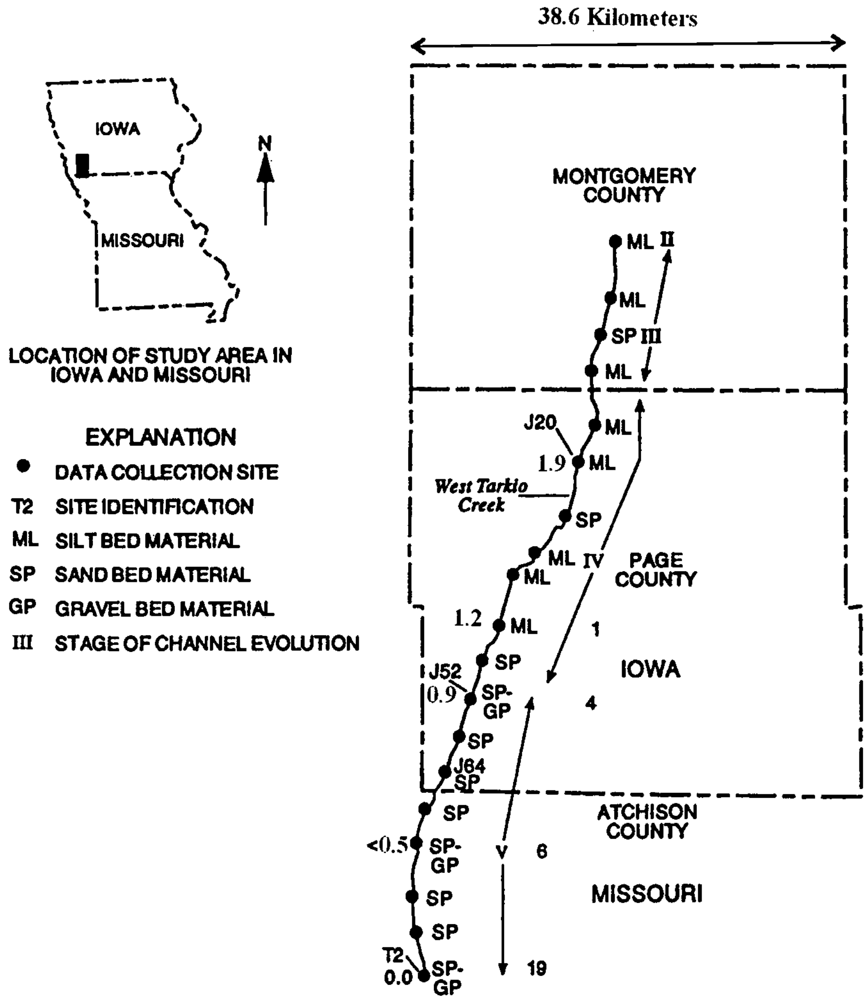

Figure 6. Map of West Tarkio Creek, Southwestern Iowa and Northwestern Missouri, Showing Stages of Channel Evolution, Dominant Bed-Material Size Class, Age of Oldest Riparian Tree (years, numbers on right), and Widening Rate (meters per year, numbers on left).

that deposition at a rate of about 0.04 m/yr was an ongoing process. Degradation trends at nine sites are shown in Figure 7. The three plots in the bottom row of the figure show that degradation along the downstream-most 18 km of channel is virtually complete. Considerable degradation continuing beyond the year 2000 can be expected along upstream reaches until the curves become asymptotic (Figure 7). An empirical model of bed-level adjustment for West Tarkio Creek is obtained by plotting the a-value coefficient (from Equation 4) against distance from the junction with Tarkio River (Figure 8). The future elevation of the channel bed, when degradation has reached a minimum, can be obtained by multiplying the a-value at a site (Figure 8) by the initial bed elevation.

Maximum degradation (minimum a-values) along West Tarkio Creek is estimated to occur near river kilometer 32.2 (Figure 8), in comparison to the Piest *et al.* (1977), observation that it would occur near the Iowa-Missouri state line (river kilometer 17.7). This is not a particularly important distinction; however, that maximum degradation occurs in the middle reaches of West Tarkio Creek as opposed to in downstream reaches as is typical of silt-bedded streams disturbed throughout their length (Simon, 1994; Piest *et al.*, 1977) attributes this to several factors including inferred differences in soil erodibility, steepness of the longitudinal profile, and the "natural evolutionary sequence" (p. 487). Degrading reaches of the channel do not have a statistically significant difference in the amount of clay or sand in the bed material to indicate different potentials for entrainment and erosion. Differences in (1) the gradient of the longitudinal profile and (2) channel morphology (stages of channel evolution) are merely a function of the migration of adjustment processes with time and reflect conditions at the time of observation. It seems probable, however, that maximum degradation should occur in the middle reaches of West Tarkio Creek because of the longitudinal distribution of available stream power in the basin. Increases in runoff rates and, consequently, stream discharges and total stream power would be

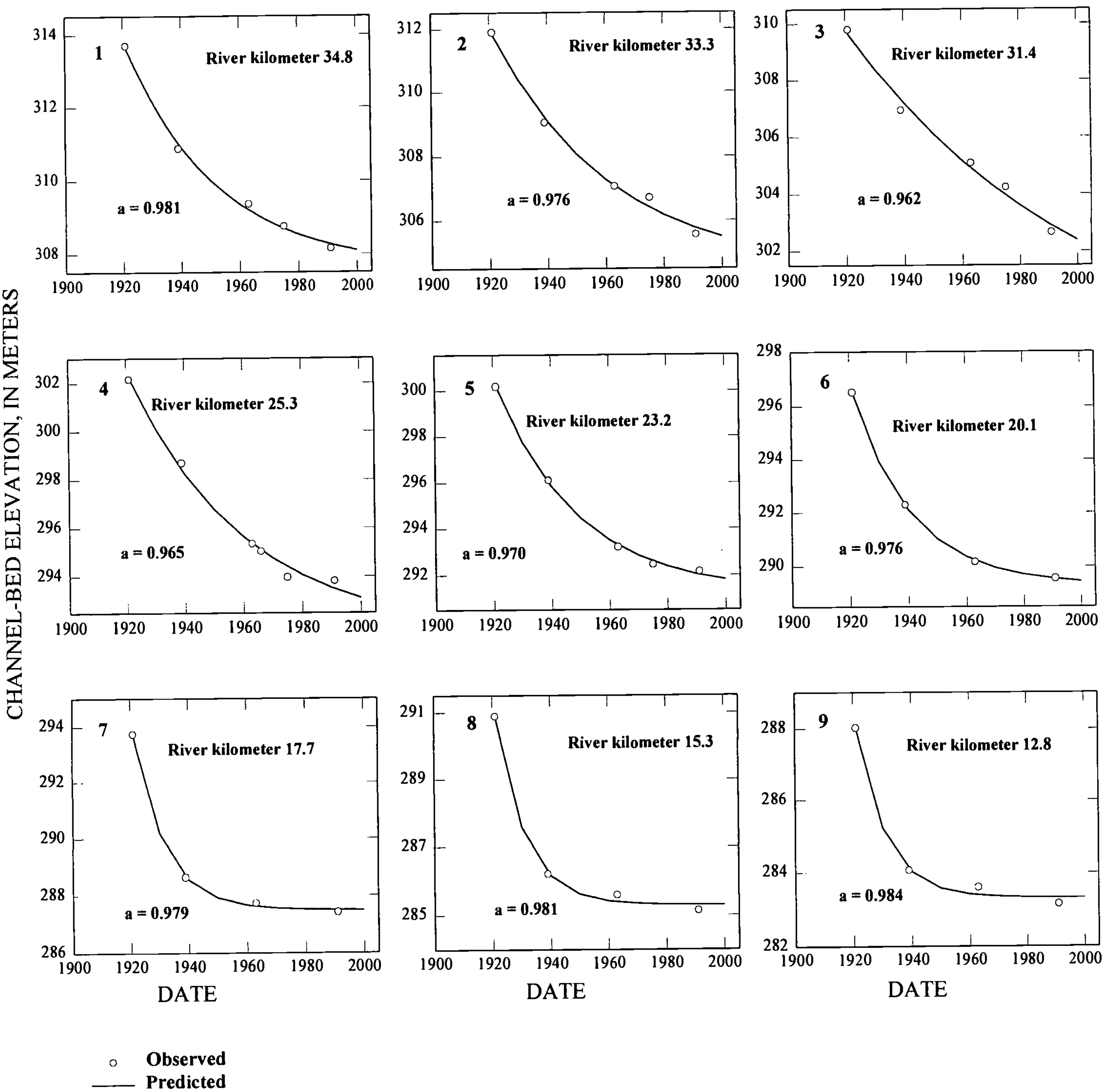

Figure 7. Trends of Degradation at Nine Sites on West Tarkio Creek Fit With Equation (4).

most effective in the middle reaches of drainage basins where available stream power generally is greatest (Graf, 1982; Lewin, 1982; Schumm *et al.*, 1984). The middle reaches would then represent the "area of maximum disturbance" where maximum amounts of degradation can be expected (Simon, 1989b, 1992, 1994) for both disturbances – the indirect changes to rainfall-runoff relations in the 1850s and the channel straightening in about 1920.

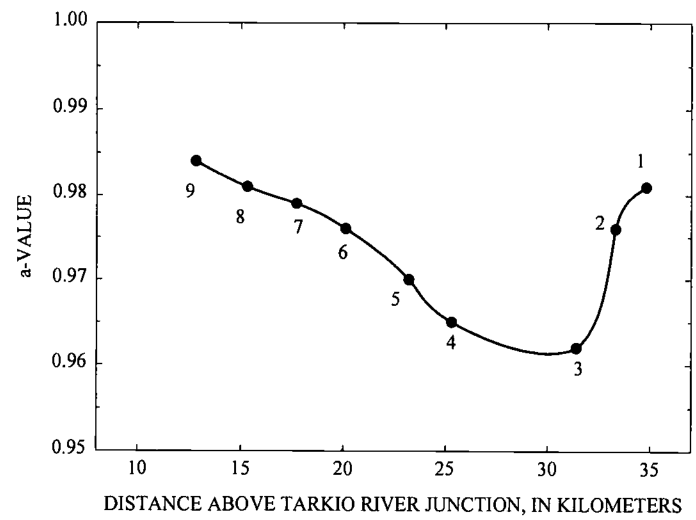

Figure 8. Longitudinal Distribution of *a*-Values (from Equation 4) Representing an Empirical Model of Bed-Level Response for West Tarkio Creek.

Channel-Width Adjustments

Changes in channel width have been and continue to be dramatic on West Tarkio Creek. Figure 9 shows increases in channel width for the period 1845-1994 at a site approximately 3.2 km south of the Iowa-Missouri state line where bed-level recovery has started. This does represent a present-day worst-case condition because channel widening has slowed as aggradation has become the dominant process on the channel bed.

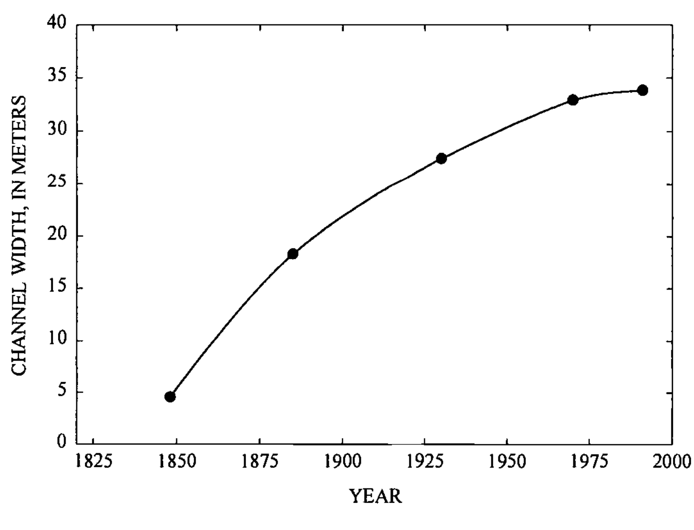

Figure 9. Changes in Channel Width During the Period 1845-1994 for a Site on West Tarkio Creek About 3.2 Kilometers South of the Iowa-Missouri State Line.

More severe bank instabilities are located further upstream. The J52 bridge over West Tarkio Creek, located 8 km north of the Iowa-Missouri state line (Figure 10a) is used as an example for applying analytic methods regarding bank instability and estimation of stable bank geometries. *In-situ* shear-strength tests at 0.9 and 1.5 m-deep were taken about 50 m downstream of the bridge. A mean cohesive strength (**c**) of 8.9 kPa and a mean friction angle (ϕ) of 29.8° were obtained. The mean, saturated bulk unit weight (γ) of two undisturbed samples of the bank material was 22.1 kN/m^2. A stability number ($\mathbf{N_s}$) of 6.90 was calculated using ϕ = 29.8°, assuming a vertical (90°) bank slope (**i**), and (Lohnes and Handy (1968):

$$\mathbf{N_s = (4 \sin i \cos \phi) / [1 - \cos (i - \phi)]} \qquad (5)$$

Critical bank height ($\mathbf{H_c}$, above which there would be mass failure) is obtained by substituting $\mathbf{N_s}$ into the following equation from Carson and Kirkby (1972):

$$\mathbf{H_c = N_s (c / \gamma)} \qquad (6)$$

For **i** = 90°, $\mathbf{H_c}$ = 2.85 m. Iterating for bank angles of 80, 70, 60, 50, and 40° results in a bank-stability chart for ambient field conditions at the J52 site (upper line; Figure 10a). This entire procedure is then repeated assuming that the banks are saturated and that ϕ = 0.0 (Lutton, 1974) to obtain $\mathbf{H_c}$ values under saturated conditions, resulting in the lower line of Figure 10a. The $\mathbf{H_c}$ values obtained range from 1.6 m at a bank angle of 90° to 4.5 m at a bank angle of 40° (Figure 10a). The effect of saturated conditions on decreasing $\mathbf{H_c}$ can be seen by drawing a vertical line anywhere on Figure 10a and comparing the difference in values at the intersection of the ambient- and saturated-condition lines.

A statistical treatment of the frequency of bank failure for the three stability classes is desirable but not possible at this time. Relative frequency is subjective, but is based on empirical field data from southeastern Nebraska, northern Mississippi, western Iowa, and, particularly, from West Tennessee. An "unstable" channel bank can be expected to fail at least annually, and possibly after each major flow event (assuming that there is at least one in a given year). "At-risk" conditions indicate that bank failure can be expected every 2-5 years, again assuming that there is a runoff event that is sufficient to saturate the channel banks. "Stable" banks by definition do not fail by mass-wasting processes. Although channel banks on the outside of meander bends may widen by particle-by-particle erosion and may ultimately lead to collapse of the upper part of the bank, for the purposes of this discussion, stable-bank conditions refer to the absence of mass wasting.

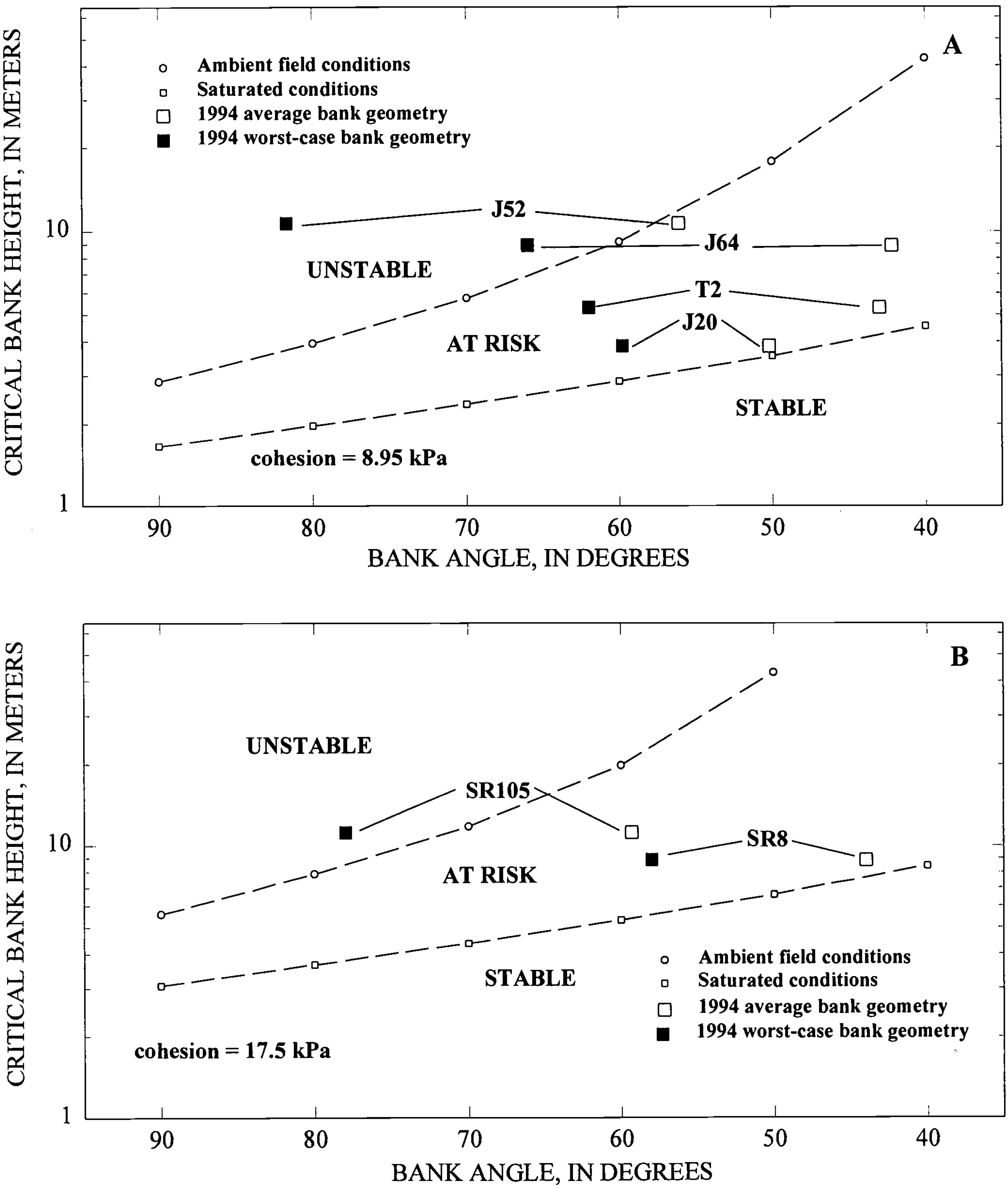

Figure 10. Bank-Stability Chart for Shear-Strength Conditions in the (A) Vicinity of the J52 Bridge Over West Tarkio Creek, Page County, Iowa; Also Used as Representative of Other West Tarkio Creek Sites and (B) Bank-Stability Chart in the Vicinity of the State Route 105 Bridge Over South Fork Big Nemaha River, Southeastern Nebraska; Also Used as Representative of Site at State Route 8.

Using the slope angles of the vertical face and upper bank to obtain an average bank angle of 62°, and using a surveyed bank height of 10.7 m (vertical distance from bank top to thalweg), channel banks at J52 plot between the at-risk and unstable zones, Figure 10a). If the angle of the "vertical face" (81°) is used to represent worst-case conditions with bank toes eroded, the banks are clearly unstable, even when relatively dry. This is probably an unrealistic scenario, but it provides the end-member stability case for unstable banks. Because the shear-strength characteristics at the J52 site are similar to average values obtained in studies of western Iowa (Lohnes and Handy, 1968) and West Tennessee (Simon, 1989c; Simon and Hupp, 1992), it seems reasonable to use the bank-stability chart (Figure 10a) to approximate stability conditions at other sites on West Tarkio Creek. Average and worst-case bank geometries are plotted for several other sites on West Tarkio Creek to show current (1994) bank-stability relations.

Shear strength and bank-geometry data for two sites on the South Fork Big Nemaha River (SFBN), southeastern Nebraska, are provided in Figure 10b to show the effects of greater cohesion on critical bank height. Note that at a bank angle of 90°, $\mathbf{H_c}$ at saturated conditions for the SFBN is greater than for a comparable bank slope under ambient field conditions for West Tarkio Creek. The cohesive strength of 17.5 kPa for the SFBN banks (almost two times greater than for West Tarkio Creek) is largely responsible for the maintenance of stable banks at greater bank heights. The range of cohesive strengths tested *in situ* in southeastern Nebraska is from 15.7 to 41.3 kPa, considerably higher than values obtained in West Tennessee (Simon, 1989c; Simon and Hupp, 1992) or in western Iowa (Lohnes and Handy, 1968), and supports the observation made earlier that the southeastern Nebraska channels maintain some of the highest banks in the region.

Generalizations about critical-bank heights ($\mathbf{H_c}$) and angles can be made with knowledge of the variability in cohesive strengths. Five categories of mean cohesive strength of the channel banks (in kPa) are created: 0 to 3.44, 3.45 to 6.89, 6.9 to 10.3, 10.4 to 13.8, and 13.9 to 25.5. $\mathbf{H_c}$ above the mean low-water level and saturated conditions are used to construct Figure 11 because failures typically occur during or after the recession of peak flows. The result is a nomograph (Figure 11) giving critical bank-heights for a range of bank angles and cohesive strengths that can be used to estimate stable-bank configurations for worst-case conditions (saturation during rapid decline in river stage) at a given cohesive strength (Simon and Hupp, 1992). For example, a saturated bank at an angle of 55° and a cohesive strength of 12.1 kPa could support a bank of no more than about 3 m (Figure 11). Because changes in bed-elevation and bank heights (flood-plain elevation minus thalweg elevation) can be obtained with Equation (4), this type of analytic solution is useful in determining the (1) timing of the initiation of general bank instabilities (in the case of degradation and increasing bank heights), (2) timing of renewed bank stability (in the case of aggradation and decreasing bank heights), and (3) bank height and angle that need to be engineered to attain a stable-bank configuration under a range of moisture conditions.

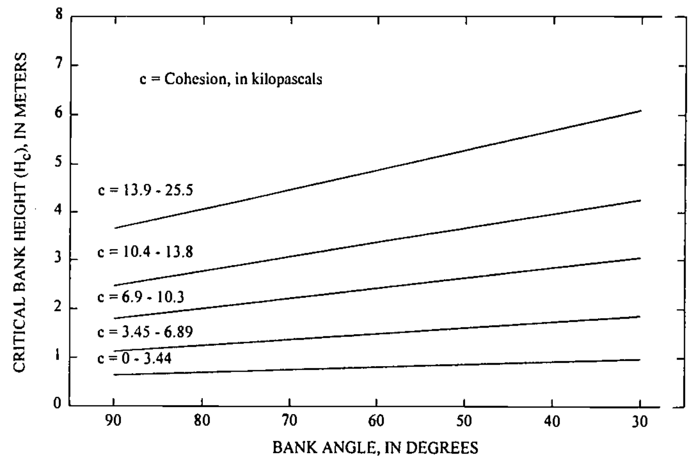

Figure 11. Critical Bank-Slope Configurations for Various Ranges of Cohesive Strengths Under Saturated (worst case) Conditions (modified from Simon and Hupp, 1992).

In most Stage IV or V channels of the loess area of the midwestern United States the re-shaping of bank slopes to regain bank stability is probably an unacceptable solution because flattening of bank angles results in additional loss of flood-plain (or terrace) lands. Similarly, it is difficult to imagine how bank heights can be reduced sufficiently by channel infilling to values less than $\mathbf{H_c}$ along the thousands of kilometers of streams that are still experiencing bank failures. The proliferation of woody vegetation on the channel banks in combination with aggradation rates that are about 60 percent less than the initial degradation rate may slowly alleviate some of this problem naturally. In places where flood-plain or terrace resources need to be protected, further human intervention may be necessary.

SUMMARY AND CONCLUSIONS

The loess area of the midwestern United States contains thousands of miles of unstable streams, predominantly responding to human modifications imposed near the turn of the 20th century. The dominant process appears to be channel widening and meander extension by mass failure. The most severe, widespread instabilities are in western Iowa where a thick loess cap and a limited supply of coarse-grained material (sand and gravel) restricts bed-level recovery by aggradation. Here relatively high streambanks combine with low cohesive strengths to sustain channel widening. Channel adjustments in West Tennessee and southeastern Nebraska are not as severe as in western Iowa. In general, channels in west-central Illinois and east-central Iowa appear to be closer to recovery than in other parts of the region.

Degradation rates for streams draining the loess hills of western Iowa and eastern Nebraska have decreased nonlinearly since 1920, approaching minimal values. In some downstream reaches, sandy alternate bars and fluvially deposited sand on low-bank surfaces indicate the beginning of bed-level recovery and the "aggradation" stage of channel evolution. This "natural" recovery process, which often occurs in other unstable stream systems following 10-15 years of degradation, was apparently delayed for an additional 55 years along some reaches in the loess area because of the lack of hydraulically-controlled (sand- or gravel-sized) source material. Finer-grained silts from eroding beds and banks were easily transported through tributary systems to the Missouri River. With loess thickness generally decreasing with distance upstream and with the degradation process migrating upstream with time, incision through the loess ultimately resulted in the exposure of coarser-grained glacial till. These deposits, thus, provided the coarse material necessary for downstream aggradation and the initial phase of channel recovery.

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LITERATURE CITED

Antosch, L. and J. Joens, 1979. Iowa's Lowhead Dams: Their Past, Present and Future Roles. Iowa State Water Resources Research Institute, No. 96, Special Report.

Ashley, G. H., 1910. Drainage Problems in Tennessee. Tennessee State Geological Survey Bulletin 3-A, pp. 1-15.

Baumel, C. P., 1994. Impact of Degrading Western Iowa Streams on Private and Public Infrastructure Costs. *In:* Stream Stabilization in Western Iowa, G. A. Hadish (Editor). Iowa DOT HR-352, Golden Hills Resource Conservation and Development, Oakland, Iowa, pp. 4-1 to 4-39.

Brice, J. C., 1966. Erosion and Deposition in the Loess Mantled Great Plains, Medicine Creek Drainage Basin, Nebraska. U.S. Geological Survey Professional Paper 352-H, pp. 255-339.

Bryan, B. A., A. Simon, G. S. Outlaw, and Randy Thomas, 1995. Methodology for Assessing Channel Conditions at Bridges in Tennessee Related to Scour Critical Conditions. U.S. Geological Survey Water-Resources Investigations Report, 94-4229, 54 pp.

Bull, W. B., 1979. Threshold of Critical Power in Streams. Geological Society of America Bulletin 90:453-464.

Carson, M. A. and M. J. Kirkby, 1972. Hillslope Form and Process. Cambridge University Press, Oxford, U.K., 475 pp.

Daniels, R. B., 1960. Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa. American Journal of Science 258:161-176.

Davis, W. M., 1902. Baselevel, Grade, and Peneplain. Journal of Geology 10:77-111.

Elliott, J. G., 1979. Evolution of Large Arroyos, the Rio Puerco of New Mexico. Colorado State University, Fort Collins, Colorado, Master of Science Thesis, 106 pp.

Emerson, J. W., 1971. Channelization: A Case Study. Science 172:325-326.

Graf, W. L., 1982. Spatial Variations in Fluvial Processes in Semi-Arid Lands. *In:* Space and Time in Geomorphology, C. E. Thorn (Editor). Publications in Geomorphology, 12, State University of New York at Binghamton, Binghamton, New York, pp. 193-217.

Hadish, G. A., 1994. Stream Stabilization in Western Iowa. Iowa DOT HR-352, Golden Hills Resource Conservation and Development, Oakland, Iowa, 198 pp.

Hidinger, L. L. and A. E. Morgan, 1912. Drainage Problems of the Wolf, Hatchie, and South Fork Forked Deer Rivers in West Tennessee. *In:* The Resources of Tennessee, Tennessee Geological Survey 2(6):231-249.

Hupp, C. R., 1992. Riparian Vegetation Recovery Patterns Following Stream Channelization: A Geomorphic Perspective. Ecology 73:1209-1226.

Hupp, C. R. and A. Simon, 1991. Bank Accretion and the Development of Vegetated Depositional Surfaces Along Modified Alluvial Channels. Geomorphology 4:111-124.

Hupp, C. R. and A. Simon, 1986. Vegetation and Bank-Slope Development. Proceedings of the Fourth Federal Interagency Sedimentation Conference, Las Vegas, Nevada, Vol. 2, pp. 5-83 to 5-92.

Ireland, H. A., C. F. S. Sharpe, and D. H. Eargle, 1939. Principles of Gully Erosion in the Piedmont of South Carolina. U.S. Department of Agriculture Technical Bulletin 633, 142 pp.

Keller, E. A., 1972. Development of Alluvial Stream Channels: A Five-Stage Model. Geological Society of America Bulletin 83: 1531-1536.

Lane, E. W., 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. Proceedings, American Society of Civil Engineers 81(795):1-17.

Lewin, J., 1982. British Floodplains. *In:* Papers in Earth Studies, B. H. Aldman, C. R. Fenn, and L. Morris (Editors). GeoBooks, Norwich,Connecticut, pp. 21-37.

Little W. C. and J. B. Murphey, 1981. Evaluation of Streambank Erosion Control Demonstration Projects in the Bluffline Streams of Northwest Mississippi. Appendix A, Stream Stability Report to Vicksburg District. U.S. Army Corps of Engineers, AD-A101-386, National Technical Information Service, 342 pp.

Lohnes, R. A. and R. L. Handy, 1968. Slope Angles in Friable Loess. Journal of Geology 76(3):247-258.

Lohnes, R. A., F. W. Klaiber, and M. D. Dougal, 1980. Alternate Methods of Stabilizing Degrading Stream Channels in Western Iowa. Iowa DOT HR-208, Department of Civil Engineering, Engineering Research Institute, Iowa State University, Ames, Iowa, 132 pp.

Luttenegger, A. J., 1987. In Situ Shear Strength of Friable Loess. *In:* Loess and Environment, M. Pesci (Editor). Catena Supplement9:27-34.

Lutton, R. J., 1974. Use of Loess Soil for Modeling Rock Mechanics. U.S. Army Corps of Engineers Waterways Experiment Station Reports S-74-28, Vicksburg, Mississippi.

Mackin, J. H., 1948. Concept of a Graded River. Geological Society of America Bulletin 59:463-511.

Moore, C. T., 1917. Drainage Districts in Southeastern Nebraska. *In:* Miscellaneous Papers, E. H. Barbour (Editor). Nebraska Geological Survey, Vol. 7, part 17, pp. 125-164.

Morgan, A. E. and S. H. McCrory, 1910. Drainage of the Lands Overflowed by the North and Middle Forks of the Forked Deer River, and the Rutherford Fork Obion River in Gibson County, Tennessee. Tennessee State Geological Survey Bulletin 3-B, pp. 17-43.

Piest, R. F., L. S. Elliott, and R. G. Spomer, 1977. Erosion of the Tarkio Drainage System, 1845-1976. Transactions, American Society of Agricultural Engineers 20:485-488.

Piest, R. F., C. E. Beer, and R. G. Spomer, 1976. Entrenchment of Drainage Systems in Western Iowa and Northwestern Missouri. Proceedings, Third Federal Inter-agency Sedimentation Conference, pp. 5-48 to 5-60.

Robbins, C. H. and A. Simon, 1983. Man-Induced Channel Adjustment of Tennessee Streams. U.S. Geological Survey Water-Resources Investigations Report 82-4098, 129 pp.

Ruhe,, R. V. and R. B. Daniels, 1965. Landscape Erosion-Geologic and Historic. Journal of Soil and Water Conservation 20:52-57.

Schumm, S. A. and R. F. Hadley, 1957. Arroyos and the Semiarid Cycle of Erosion. American Journal of Science 225:161-174.

Schumm, S. A., M. D. Harvey, and C. C. Watson, 1984. Incised Channels, Morphology, Dynamics and Control. Water Resources Publications, Littleton, Colorado, 200 pp.

Simon, A., 1994. Gradation Processes and Channel Evolution in Modified West Tennessee Streams: Process, Response, and Form. U.S. Geological Survey Professional Paper 1470, 84 pp.

Simon, A., 1992. Energy, Time, and Channel Evolution in Catastrophically Disturbed Fluvial Systems. *In:* Geomorphic Systems, J. D. Phillips and W. H. Renwick (Editors). Geomorphology 5:345-372.

Simon, A., 1989a. The Discharge of Sediment in Channelized Alluvial Streams. Water Resources Bulletin 25(6):1177-1188.

Simon, A., 1989b. A Model of Channel Response in Disturbed Alluvial Channels. Earth Surface Processes and Landforms 14:11-26.

Simon, A., 1989c. Shear-Strength Determination and Stream-Bank Instability in Loess-Derived Alluvium, West Tennessee, USA. *In:* Applied Quaternary Research, E. J. DeMulder and B. P. Hageman (Editors). A.A. Balkema Publishers, Rotterdam, The Netherlands, pp. 129-146.

Simon, A. and C. R. Hupp, 1992. Geomorphic and Vegetative Recovery Processes Along Modified Stream Channels of West Tennessee. U.S. Geological Survey Open-File Report 91-502, 142 pp.

Simon, A. and C. R. Hupp, 1986. Channel Evolution in Modified Tennessee Channels. Proceedings, Fourth Federal Interagency Sedimentation Conference, Las Vegas, Nevada, March 24-27, 1986, Vol. 2, pp. 5-71 to 5-82.

Speer, P. R., W. J. Perry, J. A. McCabe, O. G. Lara *et al.*, 1965. Low-Flow Characteristics of Streams in the Mississippi Embayment in Tennessee, Kentucky, and Illinois, With a Section on Quality of Water, by H. G. Jeffery. U.S. Geological Survey Professional Paper 448-H, 36 pp.

Thorne, C. R., 1989. Effects of Vegetation on Riverbank Erosion and Stability. *In:* Vegetation and Erosion, J. B. Thornes (Editor). John Wiley and Sons, Chichester, England, pp. 125-144.

Thorne, C. R., J. B. Murphey, and W. C. Little, 1981. Stream Channel Stability, Appendix D, Bank Stability and Bank Material Properties in the Bluffline Streams of Northwest Mississippi: Oxford, Mississippi. U.S. Department of Agriculture Sedimentation Laboratory, 257 pp.

Turnbull, W. J., 1948. Utility of Loess as a Construction Material. International Conference on Soil Mechanics and Foundation Engineering, 2nd, Rotterdam, Proceedings, Vol. 5, Section 4d, pp. 97-103.

Turnipseed, D. P. and K. V. Wilson, Jr., 1992. Channel and Bank Stability of Standing Pine Creek at State Highway 488 Near Freeny, Leake County, Mississippi. U.S. Geological Survey Open-File Report 92-112, 18 pp.

U.S. Army Corps of Engineers, 1995. Southeast Nebraska Streambank Erosion and Streambed Degradation Study, Omaha District.

U.S. Army Corps of Engineers, 1907. Index Map of the South Fork of Forked Deer River, Tennessee, from Jackson to the Mouth. Nashville, Tennessee State Archives, scale 1:48,000, 1 sheet.

Vidal, H., 1969. The Principle of Reinforced Earth. Highway Research Record, Vol. 282, pp. 1-16.

Williams, G. P. and M. G. Wolman, 1984. Downstream Effects of Dams on Alluvial Rivers. U.S. Geological Survey Professional Paper 1286, 83 pp.

Wilson, K. V., 1979. Changes in Channel Characteristics, 1938-1974, of the Homochitto River and Tributaries, Mississippi. U.S. Geological Survey Open-File Report 79-554, 18 pp.

Wilson, K. V., Jr. and D. P. Turnipseed, 1994. Geomorphic Response to Channel Modifications of Skuna River at the State Highway 9 Crossing at Bruce, Calhoun County, Mississippi. U.S. Geological Survey Water-Resources Investigations Report, 94-4000, 43 pp.

Wilson, K. V., Jr. and D. P. Turnipseed, 1993. Channel-Bed and Channel-Bank Stability of Standing Pine Creek Tributary at State Highway 488 at Free Trade, Leake County, Mississippi. U.S. Geological Survey Open-File Report 93-37, 20 pp.